Continued Investigation of Small-Scale Air-Sea Coupled Dynamics Using CBLAST Data

Dick K.P. Yue
Center for Ocean Engineering
Department of Mechanical Engineering
Massachusetts Institute of Technology
Cambridge, MA 02139
phone: (617) 253-6823 fax: (617) 258-9389 email: yue@mit.edu

Award Number: N00014-01-1-0159
http://mit.edu/vfrl/www/

LONG-TERM GOAL

Our long-term goal is to obtain a more thorough understanding of the dynamics of coupled boundary layers air-sea transfer (CBLAST) at relatively small spatial scales, by performing direct numerical simulation (DNS) and large-eddy simulation (LES) together with large-wave simulation (LWS) for both air and ocean turbulent flows with surface waves. The primary focus and an ultimate goal is to obtain the physical foundation for the characterization and parameterization of the momentum, mass and heat transfer within the atmosphere-ocean wave boundary layer (WBL).

OBJECTIVES

The scientific and technical objectives of this project are to:

- Use high-performance DNS and LES/LWS of coupled air-water wave boundary layers to fully resolve and capture the coupled air-sea-wave dynamics at ocean wave scales. Identify and assess the key transport processes within the atmosphere-ocean WBL. Elucidate the statistics, structures and dynamics of air and water turbulent flows in the vicinity of the air-sea interface.

- Provide direct comparison and cross-calibration with measurements, to help obtain physical interpretation of field data, and to develop parameterization for mass, momentum and energy transfer budget in WBL for coupled air-ocean-wave boundary modeling.

- Establish a physical basis for the characterization and parameterization of the mass, momentum and energy transfer within WBL.

APPROACH

For the DNS and LES/LWS of coupled air and ocean turbulent flows, we have developed a suite of high-performance, complementary computational methods. These include: (i) a boundary interface tracking method (BITM) for low wind speeds (<5 m/s); and (ii) an Eulerian interface capturing method (EICM) for moderate to high wind speeds (>5 m/s), where the waves steepen/break. The numerical schemes of BITM are based on boundary-fitted grids and coupled free-surface boundary conditions. The EICM is based on a level set approach. These developments are at the cutting edge of

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2007**	2. REPORT TYPE	3. DATES COVERED **00-00-2007 to 00-00-2007**
4. TITLE AND SUBTITLE **Continued Investigation Of Small-Scale Air-Sea Coupled Dynamics Using CBLAST Data**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Massachusetts Institute of Technology,Department of Mechanical Engineering,Center for Ocean Engineering,Cambridge,MA,02139**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
code 1 only

14. ABSTRACT
Our long-term goal is to obtain a more thorough understanding of the dynamics of coupled boundary layers air-sea transfer (CBLAST) at relatively small spatial scales, by performing direct numerical simulation (DNS) and large-eddy simulation (LES) together with large-wave simulation (LWS) for both air and ocean turbulent flows with surface waves. The primary focus and an ultimate goal is to obtain the physical foundation for the characterization and parameterization of the momentum, mass and heat transfer within the atmosphere-ocean wave boundary layer (WBL).

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**5**	

computational free-surface hydrodynamics. Transport of passive scalars in the coupled air-water flow system is implemented. Both the BITM and EICM codes are optimized on parallel computing platforms to provide high-resolution results in a timely manner.

The BITM method solves the incompressible Navier-Stokes equations for both air and water. Free-surface coupled boundary conditions are used at the air-water interface, with the kinematic boundary condition requiring that the interface remains a material surface, and the dynamic boundary condition specifying a stress balance across the interface. The transport of scalars is governed by a convection-diffusion equation. The governing equations are discretized using a pseudo-spectral method in the horizontal directions and a finite-difference scheme in the vertical direction. A second-order fractional-step scheme is used for the time integration of the flow field evolution, the transport of scalars, and the motion of the air-water interface.

In EICM, the air and water together are treated as a system with varying density, viscosity and diffusivity. A continuous scalar (the level set function), which represents the signed distance from the interface, is used to identify each fluid. The fluid motions are governed by the Navier-Stokes equations while the scalar is advected with the flow governed by a Lagrangian-invariant transport equation. A large wave simulation technique is used to model the effects of small surface wave fluctuations on large waves. The governing equations are discretized on an Eulerian grid using a finite-difference scheme.

WORK COMPLETED

Major progresses made during the fiscal year of 2007 include:

- Quantification of air-sea coupled turbulence kinetic energy production, transport, and dissipation processes for their modeling and parameterization.

- Elucidation of mass transport process in the air-sea coupled boundary layer and quantification of their dependence on flow structures

- Development of highly-accurate Lagrangian and Eulerian methods for the quantification of surface renewal process.

- Assessment of various surface renewal models based on extensive simulation data obtained in this study.

- Identification and quantification of dominant vortical motions in the air-sea coupled boundary layer for the parameterization of enstrophy budget.

RESULTS

During the fiscal year of 2007, significant progresses have been made towards the quantification and parameterization of transport processes in the air-sea boundary layers. The interfacial scalar transport is governed by molecular diffusion and turbulent convection processes near the interface. Figure 1 shows schematics of gas transport process near the interface and numerical simulation result of water-side turbulent vertical motions on the scalar transport and diffusion.

The dominant interfacial transfer process is surface renewal, in which fluid from the bulk of the water is convected towards the interface by upwelling. The surface renewal greatly enhances the scalar flux at the interface. Figure 2 shows the strong correlation between the scalar flux and the surface renewal strength, which is measured by surface divergence defined as horizontal divergence of flow velocity at the interface. Figure 3 shows the variation of surface divergence as a function of surface age, with the corresponding area percentage calculated. The interfacial flux during such process has also been quantified. After the surface renewal, a fluid element resides on the surface with decaying flux rate, till it encounters the next surface renewal event. An estimate of the interval of surface renewals experienced by a fluid element, i.e. the statistics of the "surface age" of a fluid element since its last surface renewal, is thus a critical measure of the intensity of scalar transport and an important parameter for its modeling.

Based on the extensive simulation data, we obtain valuable statistics of the surface renewal process. Of significant importance is that we develop a novel Lagrangian approach for tracing fluid surface elements with high accuracy, which is cross-validated with an Eulerian method. Figure 4 shows the probability density obtained from our simulation. Various theoretical results, including exponential, Gamma, normal, and lognormal distributions are examined. It is found that the distribution of surface age is not Gaussian. The exponential distribution based on the assumption of random surface replacement, which has been widely used in the literature for half a century, does not capture the entire process of the surface renewal. For young surface elements, the lognormal is a good fit, while for old elements the Gamma curve works better. Considering that the majority of surface flux occurs right after surface renewal, we conclude that the surface age distribution can be best described by the lognormal. This result establishes a physical basis for the parameterization of scalar transport at the air-sea interface.

IMPACT/APPLICATION

This study aims to obtain a fundamental understanding of the air-sea wave coupling dynamics at small scales at low wind speeds. Our work is a small yet essential part of an overall coordinated effort involving field experimentalists, air-sea modelers, and physical oceanographers to obtain improved physics-based parameterizations for air-sea interactions. Our numerical simulations provide detailed descriptions of the air-sea-wave boundary layer at small scales, and a physical basis for the modeling and parameterization of transport process within the atmosphere-ocean wave boundary layer. The simulations also provide comparison and cross-validation with field measurements. Finally, our numerical framework can be used as a powerful tool to help the interpretation and syntheses of field data, and parameterization of WBL transport process for the coupled air-ocean WBL modeling.

TRANSITIONS

The numerical datasets obtained from this project will provide useful information on physical quantities difficult to measure. Simulations in this study will provide guidance, cross-calibrations and validations for the experiments. They also provide a framework and a physical basis for the parameterization of coupled air-ocean-wave dynamics.

RELATED PROJECTS

This project is part of the ONR-sponsored Coupled Boundary Layers Air-Sea Transfer (CBLAST) DRI (http://www.whoi.edu/science/AOPE/dept/CBLASTmain.html). Our study is performed in close collaboration with Dr. Lian Shen at Johns Hopkins University and other modelers and experimentalists.

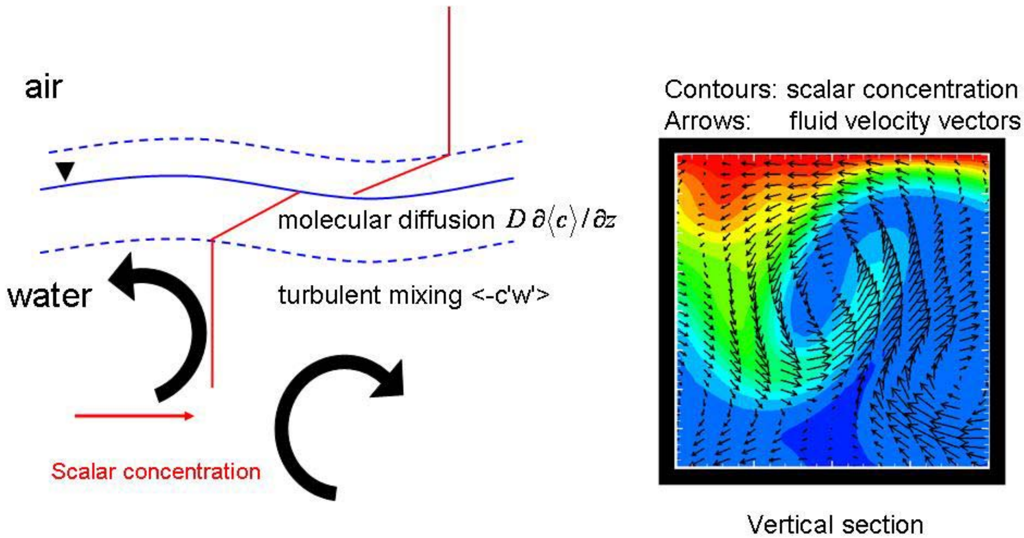

Figure 1. Left: Schematics of convection and diffusion processes of interfacial scalar transfer. Right: numerical result of scalar being convected by flow field.

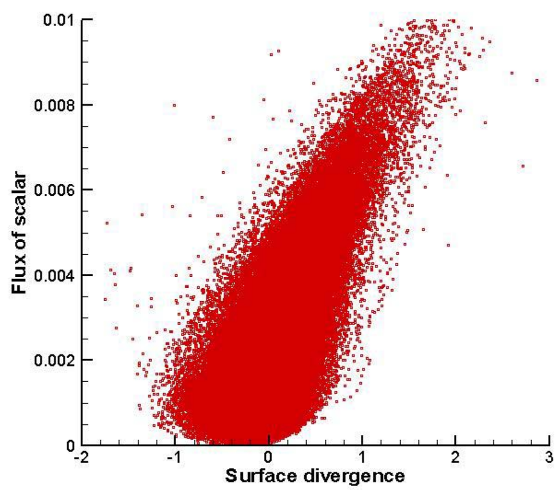

Figure 2. Correlation of surface renewal strength with flux of scalar at the air-water interface. Strength of surface renewal is measured by horizontal divergence of flow velocity at the interface.

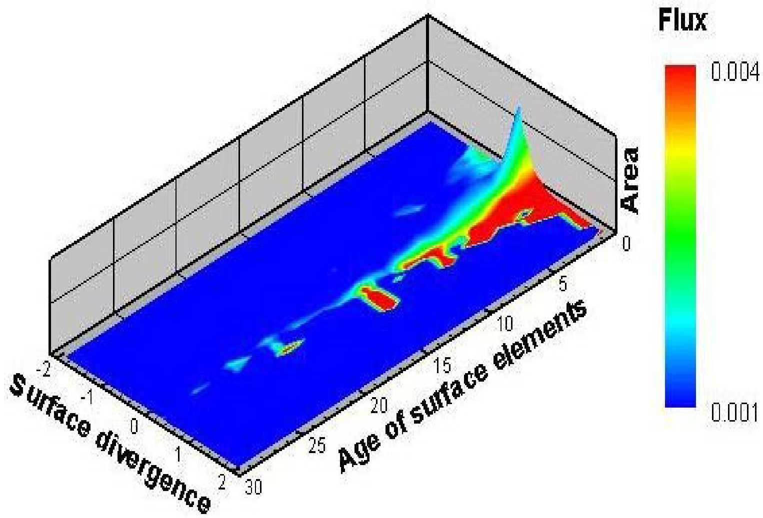

Figure 3. Correlation among surface divergence, age of surface elements, area of surface elements, and scalar flux at the interface.

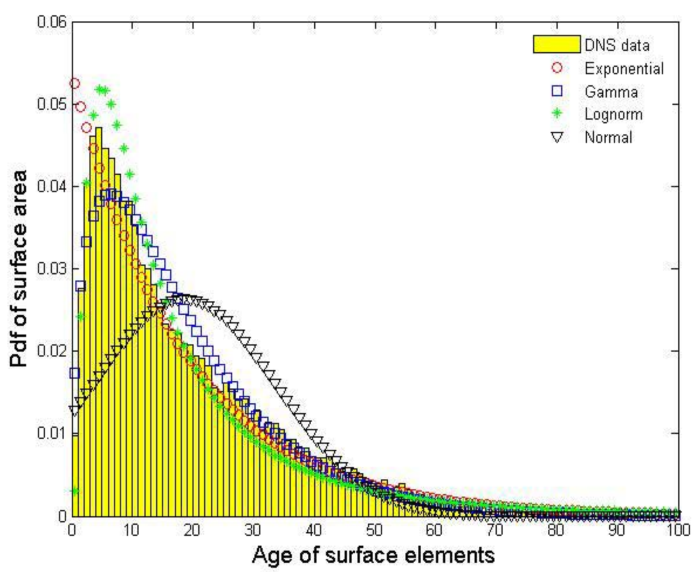

Figure 4. Probability distribution of surface element age with respect to the surface renewal process. Histogram is obtained from simulation data. Curve fittings are exponential, Gamma, lognormal, and normal, respectively.